

**The Association
of
Engineering and Shipbuilding
Draughtsmen.**

**Introduction to the Study
of Fuels and Combustion.**

By ROY T. CARTER, G.I.Mech.E.

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SESSION 1948-49.

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79

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INTRODUCTION TO THE STUDY OF FUELS AND COMBUSTION.

ROY T. CARTER, G.I.MECH.E.

With the advent of atomic power, and the realisation of its potential uses as a source of heat energy, the study of fuels and combustion might seem a little out-dated. Nevertheless, for many years to come, interest and research in the subject will be a vital necessity.

This pamphlet has been compiled in an attempt to provide an interesting and useful introduction to the study of fuels and fuel firing, particularly from the point of view of the student, who must needs refer to bulky and expensive textbooks should his interest carry him beyond the bounds of the examination syllabus.

The subject matter is divided into two main sections. The first on fuels, providing a fairly detailed examination of individual fuels, their uses and properties, as well as rudiments of fuel measurement, and the second section on combustion from a theoretical and practical viewpoint.

While every effort has been made to include as much useful and interesting information as possible, it must be remembered that the study of fuels and their combustion covers a far wider field than is possible to encompass in a pamphlet of this size. It is merely, as its title suggests, an "introduction," with the hope that the interested reader will be tempted to delve further into this important branch of engineering.

FUELS.

A fuel may be defined as a reasonably abundant substance suitable for a rapid supply of heat at a comparatively low cost. Considered as a whole, fuels fall into three main divisions :—

- (i) Solid Fuels
- (ii) Liquid Fuels
- (iii) Gaseous Fuels

—together with the all-important present day fuel, which is independent of this system of grouping—electricity.

In this country, the principal fuels are coal or coal derivatives, and petroleum. War-time and subsequent fuel conservation

has, however, made necessary the utilisation of many fuels not previously used in industry, and much experimental work has been, and is being carried out on the efficient firing of these fuels.

SOLID FUELS.

Availability.

The availability of a solid fuel is measured by :—

- (i) Calorific value.
- (ii) Moisture content.
- (iii) Volatile content.
- (iv) Ash and mineral content.
- (v) Fixed carbon content.
- (vi) Caking and swelling power.
- (vii) Weathering characteristics.
- (viii) Rate of burning.
- (ix) Grindability (if for pulverising).

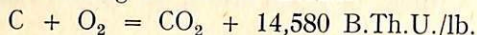
Before proceeding with the examination of individual solid fuels, it is necessary to understand the terms by which the availability of a solid fuel is measured.

Calorific Value.

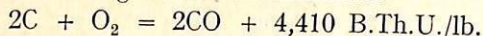
The calorific value of a fuel is usually defined as the quantity of heat liberated during complete combustion of unit weight of the fuel. The value is expressed either in calories per gramme (cals./gm.) or, as is more usual in this country, in British Thermal Units per pound (B.Th.U./lb.). (*Note.*—A British Thermal Unit is the amount of heat required to raise the temperature of 1-lb. of water through a rise equal to one Fahrenheit degree).

When carbon and hydrogen, the two chief constituents of fuels, are burnt in air, a definite amount of heat is liberated. In the case of carbon, carbon dioxide (CO_2) is formed if combustion is "complete," or carbon monoxide (CO) if the process is "incomplete," *i.e.*, when insufficient oxygen is present. This necessitates a further supply of oxygen to convert the carbon monoxide to carbon dioxide. Consider the following equations :—

Carbon burning to carbon dioxide—

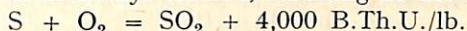


Carbon burning to carbon monoxide—



It will be noticed that when carbon is burnt to carbon monoxide, 10,170 B.Th.U./lb. of heat are lost. The heat liberated when this carbon monoxide is burnt to carbon dioxide with a further supply of oxygen is equal to this figure. When sulphur is burnt in air,

sulphur dioxide is always formed, resulting in the expression :—



In the case of hydrogen burning in air, 62,100 B.Th.U. and 9 lb. of steam are produced per pound.

If the products of combustion were cooled to the original fuel and oxygen temperature, and the steam produced from the hydrogen condensed to release its latent heat, the higher or gross calorific value of the fuel would be obtained. In practice, however, this is not feasible, and the products of combustion are released to waste at very high temperatures. If an allowance is made for this lost heat, the lower or net calorific value is obtained. The following expression shows the relationship between the two values :—

$$\text{L.C.V} = \{ \text{H.C.V.} - 1055 (m + 9H) \}$$

where H = weight of hydrogen,

and m = weight of moisture in fuel as fired.

In considering the thermal efficiency of a boiler plant for instance, it is obviously necessary to know which of the two values has been used. In this country, it is general practice to use the H.C.V. (as determined by the bomb calorimeter) in calculating the thermal efficiency, this value being easily and accurately determined by experiment. Some authorities, however, utilize the L.C.V. on the grounds that the latent heat of the water vapour is not available for use in a boiler. The effect of using the lower value is to raise the thermal efficiency by about 5%; however, the fact that present-day plant is not able to utilize this additional heat, really provides no basis for assuming an artificially increased efficiency.

Determination of Calorific Value.

The calorific value of a fuel may be determined in three ways, by :—

- (i) Calorimeter.
- (ii) "Proximate" analysis.
- (iii) "Ultimate" analysis.

The calorimeter method is preferable, and much more accurate. In this method the fuel is heated in a special apparatus, termed a "bomb" calorimeter, the heat released being imparted to a surrounding jacket of water, the rise in temperature of which can be accurately measured.

In the case of "proximate" analysis, the percentages of volatile matter and fixed carbon are determined as described later. These values are related in the following formula, giving an approximate value of C.V. :—

$$\text{Approx. C.V.} = \{ 82C + aV \} \text{ cal./gm.}$$

$$\text{Or} = \{ 147.6C + aV \} \text{ B.Th.U./lb.}$$

where C = percentage of carbon (fixed) on dry sample.

V = " " " " volatile matter " " "

a = a factor varying with the percentage of volatile matter based on the ash-free coal, and expressed by the ratio

$$\left(\frac{100V}{C + V} \right)$$

With the "ultimate" analysis method, the percentages of carbon, hydrogen, oxygen, nitrogen and sulphur are determined by chemical methods. An approximation of the calorific value may then be determined from the formulae :—

Approx. C.V.

$$(i) \text{ (Higher) } = 1/100 \{ 14,500C + 61,500 (H - 0/8) + 4000S \}$$

B.Th.U./lb.

Approx. C.V.

$$(ii) \text{ (Lower) } = 1/100 \{ 14,500C + 52,000 (H - 0/8) + 4000S \}$$

B.Th.U./lb.

where C, H, O, and S are the percentages of carbon, hydrogen, oxygen and sulphur respectively, in the fuel.

Moisture Content.

The moisture in a fuel may be of two types :—

- (i) Adherent or "free" moisture.
- (ii) Inherent moisture.

The former is due to weather action during transit and storage, the second existing in the fuel in direct relationship to the content of moisture in the surrounding atmosphere.

In solid fuels, the moisture content may vary within very wide limits, and in the case of several low-grade fuels, artificial drying is often necessary before satisfactory combustion of the fuel can be attempted.

Volatile Content.

The "volatiles" are tarry, gaseous matter driven off when coal is carbonised (*e.g.*, when raw coal is placed on a hot fuel bed). The actual volatile content of a fuel is determined by heating 1gm. of dry fuel in a closed crucible until all the gases have been driven off, then allowing the remainder to cool in the closed crucible back to the initial temperature. The loss in weight is equal to the weight of volatile matter evolved.

Ash and Mineral Content.

Ash consists of extraneous material such as clay, shale, etc., picked up during mining and transportation, and also a certain percentage of inherent ash from the original vegetable matter from which the solid fuel originated.

The ash content may be determined by heating 1gm. of dry fuel in an open crucible until combustion is complete.

Fixed Carbon Content.

When a weighed sample of the fuel has been heated in a closed crucible to drive off the volatile matter, the "coke" or residual matter, contains the inorganic material which, after complete combustion, forms the ash. The "fixed" carbon value is given by the formula :—

Fixed carbon = $100 - (\% \text{age of ash} + \% \text{age of volatile matter})$.

As well as carbon, the "coke" will contain hydrogen, nitrogen, oxygen and sulphur, and may vary in texture from a black powder to a hard, solid lump.

Caking and Swelling Power.

The caking power is the property a fuel possesses of forming a coherent coke. It may be experimentally determined by heating a sample in a special furnace to a high temperature. The appearance of the residue is then compared with a standard set of cokes.

The swelling power is determined as per British Standard Specification 1016 : 1942, the resulting cokes being also compared with a standard set.

Weathering Characteristics.

The "friability" of a fuel is the ease with which it will break down into smaller lumps after being subjected to long periods in the open air.

Coals, for example, which have been stacked for long periods in the open, may break down upon handling ; thus, when fired into a furnace much of the fuel may fall through the firebars into the ash-pit, causing quite a considerable loss.

Grindability.

Grindability is an important factor in pulverised fuel firing. The ease with which a fuel can be ground has an important bearing on the type, horse-power, etc., of the pulverising plant. Fuels with a high ash-content may cause considerable wear on the internals of the pulveriser.

COAL.

Coal is the chief source of fuel and power in this country, and in many places abroad, and may therefore be considered as the most important of the solid fuels.

Origin of Coal.

When vegetable matter dies, the tissue becomes exposed to the atmosphere and decay takes place. The cellulose (carbon

and hydrogen) is oxidised, and the resulting gaseous matter disperses into the atmosphere. If the supply of air necessary for oxidation is limited, as for instance in a marsh, or bog, the decomposition is modified, methane or marsh gas is formed and a large amount of carbon remains. This is buried under many layers of mud and sand, and is subjected to the intense pressure of the earth's crust, which, coupled with an immense period of time, produces a metamorphosis resulting in coal.

The original vegetable matter may have accumulated in one area either by water action (rivers, etc.), or, of course, may have fallen at the place of original growth.

The nature of the coal produced varies considerably, due chiefly to the nature of the original vegetable matter, the pressure and temperature to which it has been subjected, and divers other factors.

Movement of the earth's crust causes layers of the decayed vegetable matter to become separated by interspaced layers of sedimentary rocks, forming "bands" or "seams" of coal, separated by strata of clay, shale, etc.

Composition of Coal.

Coal is composed chiefly of carbon and hydrogen with small percentages of oxygen, nitrogen and sulphur, together with moisture and accumulated mineral matter.

Of the combustible portion, the carbon content may vary between 55% and 95%, the hydrogen between 3% and 6%, oxygen 1.5% and 30%, nitrogen 1% to 2%, and sulphur 0.5% to 2.5%. The moisture content may vary widely. The calorific value of coal is usually between 9,000 and 15,500 B.Th.U./lb. gross.

Generally speaking, as the values of the carbon content and heating power increase, so do the percentages of volatile matter and inherent moisture decrease. The rate of burning and the flame length vary with the volatile content, coals of low volatile content being generally slow burning with short flames, and coals of high content fast burning with long flames.

Preparation of Coal for Sale.

The percentage of coal which is washed, picked, and sized, has to-day naturally decreased, owing to the necessity of increased production with reduced labour. Quite a moderate proportion of coal, in pre-war days, was washed before sale. Many collieries, however, did not have, and still do not have, washing plant of any description.

As mined, coal varies in size from fine slacks to large lumps up to 2 ft. and includes much accumulated dirt and carboniferous shale. Coming from the pit-head, the coal is first screened to separate the larger lumps (the size of screen mesh varying con-

siderably according to local practice). These are then passed to the picking belts where the dirt, etc., is removed by hand. This coal is then suitable for sale for locomotive and domestic use.

The smaller coals passing through the screens are generally washed, to be sold for industrial purposes. Small coals are of two types :—

- (i) Sized Coals.
- (ii) Slacks.

The "sized" coals are known as "singles," "beans," "pearls," or "peas," these names being given to the various grades passing through standard mesh screens.

Slacks have various names, differing with locality, such as "dross," "smalls," "duff," "gum," etc.

Storage of Coal in Bulk.

Storage of coal in large quantities brings a very important fact to light.

Raw coal exposed to the atmosphere absorbs oxygen. This absorption is accompanied by emission of heat, and a consequent rise in temperature. Should the conditions of storage be such that dispersal of this heat to the atmosphere is not easy, a larger rise in temperature is noticed, naturally resulting in a greater absorption of oxygen. As the temperature rises, the absorption of oxygen increases rapidly, and this may continue until spontaneous combustion results. If, however, the heat evolved can be rapidly and easily dispersed, a temperature point may be reached where the dispersal and evolution of heat are balanced, thus causing no great harm.

The rate of oxygen absorption varies with the surface area of coal exposed to the atmosphere, and consequently large coals are less subject to the oxidation process than small coals, which may include a large percentage of "fines."

Suppression of oxidation may be carried out in two ways, either by well-ventilating the stack (this is often impracticable in the case of large stacks) or by suppressing the ventilation. Plenty of ventilation allows rapid dispersal of heat, while suppressed ventilation reduces the supply of oxygen.

Freshly-mined coal is more susceptible to spontaneous combustion than coal which has been stacked for some considerable time. After about six months after stacking, it may be safely assumed that the oxidation period has been passed.

TYPES OF COALS.

(i) Peat.

Peat may be regarded as the first stage in the metamorphosis of vegetable matter into coal. Its very appearance indicates its

vegetable origin, although peat excavated from well below the surface is darker in colour, and shows less vegetable traces.

The moisture content is very high, in some cases in the order of 90%, or more, and even from a well-drained bog, may contain as much as 80%. This is an important problem to be solved as regards the use of peat as a commercial fuel. Extensive drying is necessary, and special furnaces with pre-drying equipment have been experimented with in Russia and other parts of the world.

There are large deposits of peat in Scotland and Eire, and lesser known ones in England, where it supplies local domestic fuel needs.

Well-dried peat may have a calorific value of between 6,000 and 8,000 B.Th.U./lb. Its carbon content is usually from 50 to 60%, oxygen 35%, hydrogen 6%, and ash 4%, approximately.

(ii) **Lignites and Brown Coal.**

Lignites are an intermediary stage between peat and true coal. Although the two terms "lignite" and "brown coal" are mostly used synonymously, there is usually considered to be a distinct difference between the two. Lignite has a more woody structure and a high moisture content, brown coal being more mature with a lower moisture content, and a higher content of carbon.

The moisture content of both lignite and brown coal is high in relation to other coals, and may be more than 40%. Lignites are easily broken, thus difficult to transport, and break down into fines on weathering.

Although occurring only in small areas in this country, there are extensive deposits abroad, where they are used for steam raising if of sufficiently high combustible content. Lignites and brown coals burn with a long, smokey flame.

Calorific values 9,000 to 13,000 B.Th.U./lb.

Approximate composition :—50-80% carbon, 5% hydrogen, 10 to 30% oxygen, 1 to 2% nitrogen, 5 to 10% ash.

(iii) **Bituminous Coals.**

May be regarded as the third stage in the formation of coal.

Bituminous coals vary in carbon content from approximately 75 to 90%, while the moisture content is generally from 4 to 6%, as mined. Their structure frequently shows traces of vegetable origin. They are fairly brittle, and seldom break down due to weathering action.

There are many types of bituminous coal, the chief ones being known as "caking" and "non-caking" types. The caking variety are rich in hydrocarbons, being ideal for gas-making, but poor for steam raising on account of their tendency to swell and fuse into a solid, sticky mass, requiring a strong draught and constant use of firing tools.

"Steam," or non-caking, coals are, as their name implies, ideal for steam raising, showing little tendency to cake, and burning freely with a fair draught.

Modern plant developments have, however, rendered the terms "gas coals" and "steam coals" meaningless, and many and varied are the qualities of coal now being used in the gas industry, and for steam raising.

Calorific values :—

Non-caking, 14,500 B.Th.U./lb.

Caking, 14,000 B.Th.U./lb.

Approximate compositions :—

Non-caking—85% carbon, 4% hydrogen, 1.5% nitrogen,
5% oxygen, 0.5% sulphur, 5% ash.

Caking— 80% carbon, 6% hydrogen, 1.5% nitrogen,
7% oxygen, 1% sulphur, 5% ash.

(iv) **Semi-bituminous Coals and Anthracites.**

Semi-bituminous coals are a stage between the bituminous and anthracitic groups, having a carbon content 90-94%, with 23 to 10% volatile matter.

All coals with a carbon content over 94% are termed anthracites. They are hard, dense, and brittle, and show no trace of vegetable origin. Having a low volatile percentage, below 10%, anthracites ignite only with difficulty, but have a high heating value, and burn with a short, hot flame.

Calorific value—15,000 to 15,500 B.Th.U./lb.

COKE.

Coke is the solid residue remaining when coal is heated in a closed vessel at temperatures remaining over 750°F., the gaseous matter being driven off, leaving carbon and mineral matter, with small percentages of sulphur, hydrogen, nitrogen and phosphorus.

The slacks from good coking coals, when carbonised, produce a hard coke, which is used in the metallurgical industry. Coals of a higher volatile content are used in the gas-making industry, and produce a coke somewhat weaker in structure.

After the gaseous products have been evolved, the coke is removed from the retort and hand, or mechanically, sprayed with sufficient water to prevent it re-igniting when standing in air. Thus the moisture content of coke depends upon the amount of water used for quenching, and if the correct amount be used, the residual heat in the coke will evaporate the adhering water leaving the coke fairly moisture-free. Gas coke usually contains about 6% moisture, metallurgical coke 3%.

Due to the quenching process, coke has naturally a mechanically strained structure, containing many cracks which may cause it to break up on handling.

Gas coke is very porous, approximately 40 to 60%, but metallurgical coke is more dense.

Calorific value of gas coke—12,500 to 13,000 B.Th.U./lb.

LOW GRADE FUELS.

The term "low-grade" fuels had very little significance in this country until war-time and subsequent fuel conservation made necessary the consideration of their use as commercial fuels. Many low-grade fuels have been in extensive use for a good number of years in many parts of the world, where it is cheaper and easier to utilize the available by-product or waste material, than to consider the use of imported fuels.

Low-grade fuels may be divided into two distinct classes :—

- (i) Natural low-grade fuels—inferior coals, lignites, 'wood, and peat.
- (ii) Industrial and household wastes—straw, bagasse, peanut shells, sawdust, household refuse, etc.

Both classes are characterised by their high moisture content, necessitating often considerable artificial drying before firing. After drying, they are either pulverised, or burnt in specially designed furnaces with stepped or horizontal grates, and tuyere-clad walls.

The use of wood as a fuel is now mostly confined to countries with extensive forestal areas. In timber-producing countries, wood refuse is used as a medium for steam-raising, even on quite large boilers employing travelling-grate stokers. Wood refuse from joinery shops is often fed as an auxiliary fuel to furnaces burning coal.

Calorific values of wood :—

Wood refuse—5,000 B.Th.U./lb.

Wood (artificial drying)—7,000 B.Th.U./lb.

Wood (air dried)—5,600 B.Th.U./lb.

Bagasse, or sugar-cane fibre, is the waste product from the milling process of sugar manufacture, and has a calorific value of approximately 3,000 to 5,000 B.Th.U./lb. It consists chiefly of cellulose, and has a high moisture content—40 to 50%, requiring some measure of artificial drying before firing.

Many other similar industrial wastes, such as rice husks, coffee husks, spent tanbark, sorghum, maize bagasse, olive husks, grape skins, and peanut shells are also used as fuels, each requiring drying before being fed to specially arranged furnaces.

Much experimental work has been carried out during the past few years, both here and abroad, to determine the easiest and most economical method of pre-drying and burning these low-grade fuels, and so retrieving valuable heat energy from material which would otherwise go to waste. Many of these experiments have been highly successful, and utilization of low-grade fuels has done much to aid world-wide fuel conservation.

LIQUID FUELS.

Availability.

The availability of a liquid fuel is measured by :—

- (i) Calorific value.
- (ii) Viscosity.
- (iii) Specific gravity.
- (iv) Flash-point.
- (v) Pouring point.
- (vi) Ash content.

Viscosity.

The viscosity of a liquid may be defined as the measurement of the time taken for a certain quantity of the liquid to pass through a standard orifice, at a given temperature. The apparatus used to determine this figure in this country, is the Redwood Viscometer, and the measurement itself is quoted in "Seconds Redwood."

Flash-point.

The "flash-point" is the temperature at which the air space above the surface of a liquid fuel contains sufficient vapour to be ignited upon the application of a flame, the liquid existing at a standard set of conditions.

Pouring-point.

This is the minimum temperature at which the liquid will flow, measured at a standard set of conditions.

Ash Content.

Determined from the complete combustion of a weighed amount of liquid fuel, the residue being the ash. In the case of petroleum fuels, the ash content is so small that it may be considered as of no importance as regards calculations, etc.

CRUDE PETROLEUM.

Crude petroleum is the source from which the bulk of liquid fuel is obtained, the largest areas of supply being North America, Russia, the Near East and Rumania. As it issues from the well, crude petroleum may vary from a thin to a heavy, thick liquid, and may vary in colour from yellow to near black.

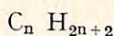
Composition.

Issuing from the oil well, crude petroleum is a mixture of solids, liquids and gases, the gaseous part being termed "natural gas." (*q.v.*).

As already outlined, fuels in general have as their main constituents carbon and hydrogen; this is so with petroleum fuels. These constituents fall into three main groups :—

- (i) Paraffins.
- (ii) Aromatics.
- (iii) Naphthenes.

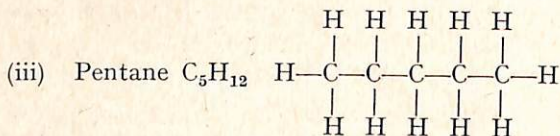
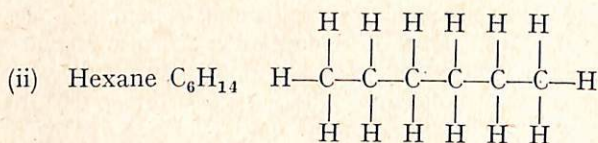
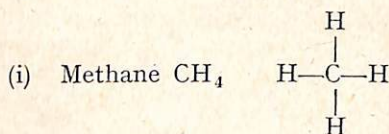
Considering each of these in turn, the paraffins have the general formula :—



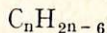
examples of which are :—

pentane C_5H_{12} ; hexane C_6H_{14} ; octane C_8H_{18} .

They are known as "chain" compounds, owing to the arrangement of the atoms in the molecule, viz. :—



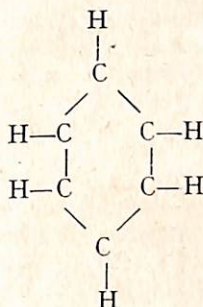
The second series, the "aromatics," have the general formula:—



examples of which are :—

Benzene C_6H_6 ; Toluene C_7H_8 ; Xylene C_8H_{10}

These are termed "ring" compounds, again owing to the atom arrangement. For instance, in the benzene molecule the atoms are arranged thus :—



The third group is the "naphthenes" group, having the general formula :—



examples of which are :—

Cyclopentane C_5H_{10} ; Cyclohexane C_6H_{12}

Methylcyclohexane C_7H_{14} .

Distillation of Petroleum.

Petroleum may thus be regarded as a complex mixture of many of the members of the three hydrocarbon groups, together with small amounts of sulphur, nitrogen and oxygen, and a small quantity of mineral ash.

Distillation direct is the oldest method of refining crude petroleum, although in pre-internal combustion engine days, kerosene, and not the petrols, was the prime objective. Distillates are divided into the following groups for marketing purposes :—

- (i) Motor gasolines.
- (ii) Solvent spirits—turpentine substitute and paint compounds.
- (iii) Burning oils—paraffin oils and kerosene.
- (iv) Gas oils—for water gas treatment, and compression ignition engines.
- (v) Lubricating oils.
- (vi) Solid paraffin waxes.
- (vii) Bitumens, or pitches.
- (viii) Distillates and residual oils from heavier fractions, used as fuel oils.

It should be noted that each of the above group is in itself a range of products, many needing considerable chemical and physical treatment before the final marketable product is obtained.

The original distillation plant, known as a "Batch still," consisted of a boiler and a condenser in which the vapours were condensed, kerosene being the object of distillation. The yield of

motor spirit by this method was very low. The modern plant contains a pipe still, and fractionating columns, each compartment in the column being kept at a higher temperature than the preceding one. Various other devices are now installed, so that to-day a very clearly defined range of products is obtainable.

Cracking.

"Cracking" is the breaking-up and rebuilding of the heavier fractions into the lighter hydrocarbons. Direct distillation drives off the lighter fractions, and then the remaining heavy fractions may be subjected to a "cracking" process, when they are split up and reformed into lighter hydrocarbons, increasing the yield of the more volatile and more valuable fractions.

Liquid Fuels for I.C. Engines.

Liquid fuels suitable for use in internal-combustion engines are of two classes :—

- (i) Volatile fuels.
- (ii) Non-volatile fuels.

The volatile fuels are used in carburettor engines with an external source of ignition, and are termed "petrols." The non-volatile fuels are used in compression-ignition engines, and comprise the so-called Diesel fuels.

Detonation, or "knocking," is an important consideration in the choice of fuels for I.C. engines. The exact reason for the phenomenon is not fully understood, but it is due to a combination of physical and chemical reactions, occurring after ignition. The "anti-knock" properties of a fuel depend largely on the proportions of the three hydrocarbon groups—paraffins, aromatics and naphthenes—previously mentioned, each of these groups differing in their tendency to detonate.

The "aromatics" are least liable to "knock," the naphthenes intermediate, and the paraffins the worst. Benzene, the chief member of the aromatic group, has a high freezing point, so that a fuel consisting purely of aromatics would be subject to freezing under extreme weather conditions. Thus, blending in various proportions is necessary to produce a suitable fuel.

"Dopes" are often added to petrols to reduce the detonating tendency, tetra-ethyl lead $Pb(C_2H_5)_4$, being the most common, coupled with a certain percentage of ethylene dibromide $C_2H_4Br_2$ to counteract the deposition of lead in the engine cylinder after combustion, the final product being commercially termed "Ethyl fluid."

Alcohol.

From the point of view of fuels, alcohol is easily produced from the destructive distillation of vegetable matter, and thus presents

an important source of fuel which is not dependent on natural deposits. Although used to some extent as a commercial fuel, it is very restricted in use in this country owing to the necessity of adding various adulterants to meet excise requirements.

"Power alcohol," consisting mainly of ethyl alcohol, and a small percentage of methyl alcohol (wood spirit), must, under excise regulations, have at least 20-25% of benzol or petrol added, together with a colouring agent before release for sale.

Alcohol is more difficult to ignite than petrol, and has a much lower heating value, thus increasing the relative fuel consumption of the engine.

Benzol.

The chief source of benzol is the carbonisation of coke, and it consists chiefly of benzene and toluene. As a fuel, it is important as a substitute for petrol in I.C. engines, necessitating practically no alteration to the existing plant. It is, however, more usually added to petrol, and not employed on its own.

Shale Oil.

Shale oil is a natural petroleum obtained from the distillation of shale, the oil-bearing varieties of which are found in Gt. Britain, as well as in Australasia. The distillation produces a heavy crude oil, which upon retreatment yields motor spirit, lubricating oils, kerosene and paraffin wax.

Coal Tar Oils.

Coal tar fuels are byproducts of the high temperature carbonisation of coal, and in this country are usually produced at the gas works, from vertical or horizontal retorts, and by coke-oven plant. They are available in various grades, the chief difference between the grades being the atomization temperature, the lowest 50°F. (known commercially as C.T.F. 50), and the highest approximately 400°F. (C.T.F. 400).

In general, coal tar fuels have a low sulphur content (up to 1% maximum), and a negligible content of ash, the heating values ranging between 16,000 and 17,000 B.Th.U./lb. gross, while the carbon content is in the order of 90%.

During transport and handling, coal tar fuels require heat-insulated tanks and pipe-lines, although the grade C.T.F. 50, being liquid down to 32°F., can be transported without trouble.

GASEOUS FUELS.

Coal Gas.

Coal, or "town," gas produced by the distillation of coal, is obtained from either of two sources :—

- (i) Gasworks.
- (ii) Coke-ovens.

At the gas works, the coal gas is the prime objective, the resulting coke being a byproduct, while at the coke-oven plant, the reverse is the case, gas being the byproduct.

The chief constituents of coal gas are hydrogen and methane, usually about 50%, and 30%, respectively, together with other gaseous hydrocarbons; although the actual composition, together with the calorific value, depends largely on the method of manufacture.

The following is the composition of a Midland town gas :—

Carbon dioxide	CO ₂	—4%
Carbon monoxide	CO	—10.4%
Oxygen	O ₂	—6%
Methane.	CH ₄	—24.9%
Hydrogen	H ₂	—48%
Ethylene	C ₂ H ₄	—2.8%
Remainder non-luminous.		

The calorific value of coal gas is controlled by Act of Parliament, the gas undertaking specifying the calorific value at which it will supply gas. Independent tests are periodically made to ensure adherence to the stipulated figure. The usual value, in this country, is between 400 and 500 B.Th.U./cu. ft. gross.

The gas is sold to consumers by the “therm,” this being the equivalent of 100,000 B.Th.U. The number of cubic feet of gas equal to a therm is given by the expression :—

$$\text{Cu. ft. per therm} = \frac{100,000}{\text{declared C.V.}}$$

Although once produced solely for purposes of illumination, coal gas has had increasing uses industrially during the past twenty years. As a medium for large-scale steam raising, the expense of coal gas firing is greater than for solid fuel, and it is thus used chiefly for firing small metallurgical and industrial furnaces, and for hot water heating installations.

Natural Gas.

Natural gas is obtainable in the oil-producing regions, and is the gaseous matter issuing with crude petroleum. Its composition varies with the locality, but its high heating value, due to the low percentage of non-combustible gases, makes it of considerable importance.

The chief constituent is methane CH₄, together with lesser percentages of ethane C₂H₆, propane C₃H₈, the butanes C₄H₁₀, and traces of carbon dioxide, hydrogen sulphide, and nitrogen.

The calorific value of natural gas is in the region of 800 B.Th.U./cu. ft. gross (at S.T.P.).

Producer Gas.

Producer gas is characterised by the large percentage of inert gases it contains, giving a rather low calorific value (130–160 B.Th.U./cu. ft. gross at S.T.P.).

The following is an average composition :—

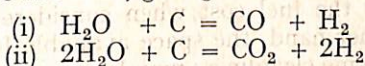
Hydrogen	H ₂	—14%
Carbon monoxide	CO	—25%
Carbon dioxide,	CO ₂	—5%
Nitrogen	N ₂	—55%
Methane	CH ₄	—1%

Producer gas is manufactured by blowing a suitable mixture of air and steam through a bed of hot coke or coal. If coal be used, the aforementioned constituents will be accompanied by small percentages of other hydrocarbons, due to the distillation of the gaseous matter from the coal.

Although of low calorific value, producer gas requires less air for combustion than coal gas, and by preheating both the gas and the air, approximately the same furnace temperatures can be obtained.

Water Gas.

Water gas is manufactured as follows. Steam is blown through a bed of white-hot coke, giving rise to the chemical reactions :—



Both these reactions absorb heat, reaction (ii) occurring at somewhat lower temperatures. When the percentage of carbon dioxide in the resulting gas becomes excessive, the steam is turned off, an air blast turned on, and the cycle repeats itself.

Water gas has a calorific value of approximately 300 B.Th.U./cu. ft. gross, and consists chiefly of hydrogen and carbon monoxide, burning with a non-luminous blue flame. The latter gives rise to the term “blue” water gas.

The application of water gas as a fuel is somewhat limited. It is used in the chemical industry as a source of hydrogen, but its principal use is by gas undertakings as a means of making town gas.

Carburetted Water Gas.

This is water gas which has been enriched by spraying in gas oil, resulting in a gas of considerably higher calorific value (500 B.Th.U./cu. ft. gross). This is then added to town gas, and the making of carburetted water gas forms an important operation in the town gas industry.

Mond Gas.

Mond gas is a special type of producer gas from gas plants where the recovery of ammonia is the criterion of operation.

Blast Furnace Gas.

This is an important byproduct of the iron and steel industry. Iron ore is smelted with coke in the blast furnace, the air blast injected during the process reacts with the coke forming carbon monoxide. Part of the carbon monoxide further reacts with the iron ore forming carbon dioxide. The resulting product is similar to producer gas in composition, but with a higher carbon dioxide content.

Blast furnace gas is used for heating coke ovens, as an auxiliary fuel for steam-raising, and may also be used in gas-engines, although the removal of the high dust content is necessary before use.

The calorific value is generally low (50-100 B.Th.U./cu. ft. gross), thus preheating of both the gas itself, and the air for combustion is necessary in order to produce a high flame temperature.

COMPARISON OF FUELS.

The considerations necessary before selecting a fuel suitable for a certain installation are many and varied, perhaps the greatest being the cost. Initial cost of plant and cost of maintenance may be outweighed by the fuel cost when considered on output efficiency. On the other hand, the space available for the plant, or the necessity for extreme cleanliness may have to be the deciding factor.

The following notes are intended to give a general idea of the considerations necessary before deciding on a certain type of fuel, although it must be understood that it is merely a generalisation.

(i) **Solid Fuels.**—Low cost. Combustion efficiency depends more on the plant than the fuel. Dust, ash and smoke. Large space required for bulk storage. Wharf or rail siding facilities. Bunkers, conveyors, elevators. Weighing machinery. Conveyors for ash removal. Heavy plant maintenance costs. Overall plant efficiency low. Furnace temperature control difficult, especially with hand firing.

(ii) **Liquid Fuels.**—Cost higher than solid fuels. Storage tanks and pipe-lines required. Possibly heating apparatus. Maintenance charges low. Efficient combustion and easy flame control. Cleanliness in boiler house as well as no dust, ash, and very little smoke.

(iii) **Gaseous Fuels.**—Cost generally higher than liquid or solid fuels. No handling charges. Pipe-lines required. Low

maintenance costs. Can only be stored in very limited quantities. Efficient combustion and easy flame control. No dust, ash, or smoke.

(iv) **Electricity.**—High Cost. Limited application as a fuel. No handling charges. Cables, transformers, switchgear required. Cannot be stored. Easy control. Overall efficiency approaches 100%.

(v) **Pulverised Fuel.**—Low fuel cost. Handling plant, etc., similar to that for solid fuels. Heavy plant maintenance charges. Pulverising and associated plant required, possibly drying plant. Dust and ash removal plant required. High furnace temperature. Efficient combustion. Easy control.

COMBUSTION.

Combustion—(Theory).

Combustion is the chemical combination of certain substances with the oxygen of the atmosphere, accompanied by the evolution of heat. If the combustibles of a fuel completely unite with the oxygen, then the maximum heat release from the fuel will be obtained, and the combustion will be "complete."

During the process of combustion, carbon combines with oxygen to form carbon dioxide, or, if the process is "incomplete," carbon monoxide is formed. Hydrogen combines with the oxygen to form water vapour. Thus, all fuels solid, liquid, or gaseous, have their combustible portions turned into gases during combustion, and the ultimate composition of these gases depends on the correct mixing of air and fuel.

The technique of combustion, then, is to ensure maximum heat release, and minimum loss, from the fuel.

Chemical Principles and Minimum Air Required.

Being a chemical process, combustion follows definite chemical laws, and the process may be expressed by the use of simple chemical equations, from which the theoretical quantity of air required for combustion may be calculated. Before proceeding with this, however, it is necessary to understand the fundamental principles from which these chemical formulae and equations are derived.

Fuels are composed of certain substances, carbon, hydrogen, nitrogen, oxygen, sulphur, etc. These are termed elements, an element being a substance which has never been divided into two or more parts having different properties.

The atom is the smallest part of a substance which can take part in a chemical reaction, and is denoted by one or more letters, viz. :—

H—represents 1 atom of hydrogen.

C— " " " " carbon.

Fe— " " " " iron.

O— " " " " oxygen.

Hg— " " " " mercury.

The molecule, which is regarded as the smallest particle of matter capable of independent existence, is composed of a group of atoms. Thus, H_2O represents one molecule of water, consisting of two atoms of hydrogen chemically combined with one atom of oxygen; and CO represents one atom of carbon monoxide, consisting of one atom of carbon combined with one atom of oxygen.

Molecules of elements may be monatomic (*i.e.*, one atom per molecule, like carbon), or diatomic (2 atoms per molecule, like hydrogen and many gases).

The relative weights of atoms have been calculated and are tabulated in the Table of Atomic Weights. The atomic weight of oxygen is 16, carbon approximately 12, and hydrogen approximately 1. Knowing the atomic weights, the molecular weights may easily be calculated, *e.g.* :—

Water (or Steam). Chemical Formula H_2O .

Molecular weight = $(2 \times 1) + 16 = 18$.

Carbon Dioxide. Chemical Formula CO_2 .

Molecular weight = $12 + (2 \times 16) = 44$.

Methane. Chemical Formula CH_4 .

Molecular weight = $12 + (4 \times 1) = 16$.

Ethylene. Chemical Formula C_2H_4 .

Molecular weight = $(2 \times 12) + (4 \times 1) = 28$.

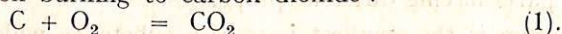
No element can combine with any other element in any proportion by weight, other than its atomic weight, or simple multiples of this.

The following chemical law is also important—"equal volumes of all gases under the same conditions of pressure and temperature contain the same number of molecules." This is known as Avogadro's Hypothesis, and may be expressed more simply by saying that the molecular weight in pounds of any gas occupies 360 cu. ft. at conditions of standard temperature and pressure ($0^\circ C$ and 760mm. of mercury). Although 360 cu. ft. is an approximation, it is sufficiently accurate for most calculations.

From the above law, it will be seen that 2 lb. of hydrogen, 32 lb. of oxygen, and 44 lb. of carbon monoxide all occupy 360 cu. ft. at S.T.P.

Consider now the equations of the process of combustion :—

Carbon burning to carbon dioxide :—



Carbon burning to carbon monoxide :—



Carbon monoxide burning to carbon dioxide :—
 $2\text{CO} + \text{O}_2 = 2\text{CO}_2$ (3).

Hydrogen burning to water vapour :—
 $2\text{H}_2 + \text{O}_2 = 2\text{H}_2\text{O}$ (4).

Sulphur burning to sulphur dioxide :—
 $\text{S} + \text{O}_2 = \text{SO}_2$ (5).

In equation (1), it is shown that one molecule of carbon containing one atom, combines with one molecule of oxygen containing two atoms, to form one molecule of carbon dioxide containing three atoms. Therefore oxygen burns with carbon to form an equal volume of carbon dioxide. Knowing the atomic weights, then 12 units by weight of carbon combine with 32 units by weight of oxygen, to form 44 units by weight of carbon dioxide.

“Units by weight” may be in grams, pounds, tons, etc., providing the same units are used throughout.

In equation (4), two molecules of hydrogen combine with one molecule of oxygen to form one molecule of water vapour, or, one volume of hydrogen combines with half its volume of oxygen to form one volume of water vapour.

From the foregoing, it will be noticed that the weights of the elements before and after the chemical change do not vary, although the volumes may do so, as in the case of equation (4).

It is thus a simple matter, knowing the chemical composition of a fuel, to determine the theoretical quantity of oxygen required to perform the chemical changes in equations 1 to 5.

The composition of atmospheric air is approximately as follows :

	By Weight	By Volume
Oxygen,	23%	21%
Nitrogen,	77%	79%

The nitrogen plays no part in the actual combustion, it is an adulterant, and has to be heated up to the temperature of the other gases involving some loss of heat, and also tends to slow up the rate at which the oxygen can be brought into contact with the combustible portion of the fuel.

The above percentages enable the theoretical weight or volume of air required per lb. of fuel to be determined by multiplying the oxygen value by 100/23 (or 4.35) and 100/21 (4.76) respectively. There is usually a discrepancy between the amounts of air by weight and by volume due to the fact that gases do not obey Avogadro's Law exactly, and due to the inaccuracy of the weight and volume ratios.

Products of Combustion.

The products of combustion of any fuel consisting of carbon and hydrogen are carbon dioxide and water vapour. If com-

bustion is "incomplete," carbon monoxide will be present, although in practice this should be avoided, due to the large quantity of heat lost (q.v.). Sulphur dioxide will be present if the fuel contains sulphur.

Thus fuels, whether solid, liquid, or gaseous, ultimately become gases after combustion. These gases are termed "flue" or "waste" gases.

From the given composition of a fuel, by applying the chemical principles previously outlined, it is possible to determine the percentage composition of the flue gases.

Available Hydrogen.

Certain fuels contain a percentage of oxygen in their composition, and since this oxygen is assumed to be already combined with part of the hydrogen in the fuel, an allowance must be subtracted equal to the oxygen present. This allowance is equal to one eighth of the oxygen content. The remaining hydrogen, termed the "available" hydrogen is given by the expression :—

$$\text{Available hydrogen} = \left\{ \text{total hydrogen} - \frac{\text{oxygen}}{8} \right\} = \left\{ H - O/8 \right\} \text{ lb.}$$

Calculation of Composition of Flue Gases.

Consider a coal having the following percentage composition by weight :—

Carbon	70%	Sulphur	2%
Hydrogen	5%	Moisture	10%
Oxygen	5%	Ash	7%
Nitrogen	1%		

Then the theoretical quantity of air required per lb. of fuel will be calculated as follows :—

$$\text{Available hydrogen} = H - O/8 = .05 - .05/8 = .044 \text{ lb.}$$

$$\text{Oxygen required by hydrogen} = .044 \times 8 = .352 \text{ lb.}$$

$$\text{,, ,, ,, carbon} = .700 \times 2.67 = 1.869 \text{ lb.}$$

$$\text{,, ,, ,, sulphur} = .02 \times 1 = .020 \text{ lb.}$$

$$\therefore \text{Total weight of oxygen per lb. of fuel,} = 2.241 \text{ lb.}$$

$$\therefore \text{Total air required per lb. of fuel} = 2.241 \times 4.35 = 9.75 \text{ lb.}$$

$$\text{Density of air at S.T.P. (32°F. 30" bar)} = .0807 \text{ lb. per cu. ft.}$$

$$\therefore \text{Volume of air required} = \frac{9.75}{.0807} = 121.8 \text{ cu. ft. at 32°F. and 30" bar.}$$

$$\text{Nitrogen supplied per lb. of coal} = 9.75 - 2.337 = 7.51 \text{ lb.}$$

Then products of combustion will be :—

Carbon dioxide	$= 0.7 \times 3.67$	$= 2.569$ lb.
Sulphur dioxide	$= 0.02 \times 2$	$= .040$ lb.
Nitrogen	$= 7.51 + .01$	$= 7.520$ lb.
Water (or Steam)	$= .05 \times 9$	$= .450$ lb.
Ash	$= .07$	$= .070$ lb.
Plus moisture in coal	$= .10$	$= .100$ lb.

$\therefore$ Total products per lb. of coal $= \underline{\underline{10.749}}$ lb.

Calculations for gaseous fuels may be carried out in a similar manner, except that they are usually calculated on a volume basis.

Tables I. and III. give values for oxygen, air, and products of combustion for the main constituents of solid and gaseous fuels.

TABLE I.

Constituent and reaction.	Per Cu. ft. of Fuel.			Per Cu. ft. of Fuel.		
	Vol. of Oxygen.	Vol. of Air.	Vol. of Product.	Wt. of Oxygen.	Wt. of Air.	Wt. of Product.
HYDROGEN $2\text{H}_2 + \text{O}_2 = 2\text{H}_2\text{O}$ 4 32 36 720 360 720	$\frac{360}{720} = 0.5 \text{ cu. ft.}$	$0.05 \times 4.76 = 2.38 \text{ cu. ft.}$	$\frac{720}{720} = 1 \text{ cu. ft.}$	$\frac{32}{720} = 0.0445 \text{ lb.}$	$0.0445 \times 4.35 = 0.1935 \text{ lb.}$	$\frac{36}{720} = 0.05 \text{ lb.}$
CARBON MONOXIDE $2\text{CO} + \text{O}_2 = 2\text{CO}_2$ 56 32 88 720 360 720	$\frac{360}{720} = 0.5 \text{ cu. ft.}$	$0.05 \times 4.76 = 2.38 \text{ cu. ft.}$	$\frac{720}{720} = 1 \text{ cu. ft.}$	$\frac{32}{720} = 0.0445 \text{ lb.}$	$0.0445 \times 4.35 = 0.1935 \text{ lb.}$	$\frac{88}{720} = 0.122 \text{ lb.}$
MARSH GAS (Methane) $\text{CH}_4 + 2\text{O}_2 = \text{CO}_2 + 2\text{H}_2\text{O}$ 16 64 44 36 360 720 360 720	$\frac{720}{360} = 2 \text{ cu. ft.}$	$2 \times 4.76 = 9.52 \text{ cu. ft.}$	$\frac{360}{360} = 1 \text{ cu. ft.}$ $\frac{720}{360} = 2 \text{ cu. ft.}$	$\frac{64}{360} = 0.178 \text{ lb.}$	$0.178 \times 4.35 = 0.774 \text{ lb.}$	$\frac{44}{360} = 0.122 \text{ lb.}$ $\frac{36}{360} = 0.1 \text{ lb.}$

From the foregoing Table I., a simplified table may be drawn up, viz.:—

TABLE II.

Constituent.	Cu. ft. per Cu. ft. of Constituent.		
	Oxygen Required.	CO ₂ Formed.	H ₂ O Formed.
CARBON MONOXIDE	0.5	1.0	—
HYDROGEN	0.5	—	1.0
MARSH GAS	2.0	1.0	2.0
OXYGEN	—	—	—
CARBON DIOXIDE	—	—	—

TABLE III.

Constituent and Reaction.	Per lb. of Fuel.			Per lb. of Fuel.		
	Wt. of Oxygen.	Wt. of Air.	Wt. of Product.	Vol. of Oxygen.	Vol. of Air.	Vol. of Product.
HYDROGEN	$\frac{32}{4}$	8×4.35	$\frac{36}{4}$	$\frac{360}{4}$	90×4.76	—
$2\text{H}_2 + \text{O}_2 = 2\text{H}_2\text{O}$	= 8 lb.	= 34.80 lb.	= 9 lb.	= 90 cu. ft.	= 428.4 cu. ft.	
4 32 36						
720 360 —						
CARBON	$\frac{32}{12}$	2.67×4.35	$\frac{44}{12}$	$\frac{360}{12}$	30×4.76	$\frac{360}{12}$
$\text{C} + \text{O}_2 = \text{CO}_2$	= 2.67 lb.	= 11.6 lb.	= 3.67 lb.	= 30 cu. ft.	= 142.8 cu. ft.	= 30 cu. ft.
12 32 44						
— 360 360						
SULPHUR	$\frac{32}{32}$	1×4.35	$\frac{64}{32}$	$\frac{360}{32}$	11.25×4.76	$\frac{360}{32}$
$\text{S} + \text{O}_2 = \text{SO}_2$	= 1 lb.	= 4.35 lb.	= 2 lb.	= 11.25 cu. ft.	= 53.5 cu. ft.	= 11.25 cu.ft.
32 32 64						
— 360 360						

Similarly, a second simplified table may be drawn up, viz :—

TABLE IV.

Constituent.	Product.	Lbs. per lb. of Constituent.	
		Oxygen Required.	Weight of Product.
HYDROGEN	WATER VAPOUR	8.0	9.0
CARBON	CARBON DIOXIDE	2.67	3.67
SULPHUR	SULPHUR DIOXIDE	1.0	2.0

Excess Air.

The preceding calculations have been based on the theoretical amount of air required for complete combustion of one pound of solid fuel, or one cu. ft. of gaseous fuel. In actual practice, the theoretical quantity is insufficient for complete combustion, and additional air must be supplied. This is termed "excess" air.

In calculations on the composition of flue gases, this additional air must be included, as the further supply of nitrogen and oxygen will obviously increase the weight of the products of combustion.

When firing coal, the quantity of excess air required is generally not in excess of 50%, whereas with oil fuel 15% may be sufficient. Gaseous fuels require much less, generally in the region of 10%, while powdered fuel has been satisfactorily burnt with less than 20%. The actual amount, however, is directly dependent on the method of firing, hand-fired plants often operating with 100% or more.

Determination of Excess Air Supplied from Analysis of Dry Products of Combustion.

Analysis of the products of combustion (or flue gases) is carried out by passing a sample of the gases through various solutions of chemicals in water. The water vapour content of the gases therefore becomes condensed, and the sulphur dioxide dissolved, leaving CO_2 , N_2 and CO , together with O_2 if large quantities of excess air be supplied. These are measured and expressed as a percentage of the total dry flue gases.

The quantity of excess air supplied may be determined approximately thus :—

Let actual percentage of CO_2 in flue gases as determined by analysis be C_A .

Let theoretical percentage of CO_2 be C_T .

Then, percentage excess air supplied by volume

$$= \left\{ \left(\frac{C_T - C_A}{C_A} \right) \times 100 \right\} \text{ approx.}$$

Combustion in Practice.

As previously stated, the technique of combustion is to secure maximum heat release, and minimum loss of overall plant efficiency.

The basic requirements to secure efficient combustion are, that the air and fuel be brought together in the correct quantities, and under the correct conditions, with adequate allowance for time, temperature, and turbulence, so that the combustion process may be fully completed within the combustion space.

The correct mixing of the fuel and air is the function of draught, and the various arrangements for securing adequate draught will now be examined.

Draught.

Draught may be scientifically defined as the small pressure difference which causes a flow of gases to take place between two points. From the point of view of combustion, it is the flow of gases through a furnace or boiler, and is usually measured in inches of water on a U-tube manometer or similar instrument.

The actual quantity of draught required varies considerably according to the type of installation, and each type should be considered purely on its own merits. The amount of draught required is dependent upon :—

- (i) Type of fuel fired and rate of combustion.
- (ii) Depth of fuel bed to be penetrated (solid fuels).
- (iii) Design of flues.
- (iv) Size, etc., of economisers and other auxiliary equipment to be installed in the flues.

Inefficient combustion is often the result of insufficient draught, or failure to make proper use of the air supply available, and unless due attention be paid to the question, the overall thermal efficiency of the plant will be greatly impaired.

There are three main types of draught system :—

- (i) Induced Draught.
- (ii) Forced Draught.
- (iii) Balanced Draught.

These first-named may be further sub-divided into "natural" and "accelerated."

Natural Draught.

The oldest form of providing natural draught is by means of a chimney, but this system has its limitations. The draught produced by a chimney is entirely dependent on the height of the chimney and the temperature of the flue gases ; and, as the chimney height obviously has limits, the flue gas temperature must be increased if greater draught be required, resulting in a higher release of heat to atmosphere, and a consequent lowering of efficiency.

Ease of construction, no auxiliary plant required, and long life with little or no maintenance, are advantages of the chimney, against which must be set the disadvantages of little flexibility of draught, and the utter dependency on external air conditions.

The intensity of chimney draught is the result of the column of hot gases rising up the chimney, and a second column of cold air, of similar cross-sectional area, descending to the air intake, the difference in weight between the two tending to cause the hot gases to rise, and the heavier cold air to descend. Thus, the chimney system may be likened to a huge U-tube, the two columns of gas and air forming the vertical limbs, and the furnace and flues the lower, horizontal limb.

The height of chimney required to induce a certain draught is given by the formula :—

$$H = \frac{d}{\frac{7.6}{(t_1 + 460)} - \frac{7.9}{(t_2 + 460)}}$$

where H = height of chimney in feet.

d = draught in inches W.G.

$(t_1 + 460)$ = absolute outside air temperature (*i.e.*, $t_1 = 60^\circ\text{F.}$)

$(t_2 + 460)$ = mean absolute temperature of the flue gases.

7.6 & 7.9 = the weights of a 100 cu. ft. of air and gas at 60°F.

The cross-sectional area of chimney to pass a certain weight of flue gases may be obtained from the formula :—

$$A = \frac{W S}{V}$$

where A = cross-sectional area of chimney in sq. ft.

W = weight of flue gases per second in lbs.

S = specific volume of flue gases at chimney temperature and pressure conditions.

V = gas velocity in ft./sec.

Accelerated Induced Draught.

Draught may also be induced by installing an induced draught fan, or ring of steam jets at the chimney base. If this method be used, the chimney height is governed only by site requirements, and not by draught required.

The locomotive boiler is an example of a steam jet placed at the chimney base, the steam in this case being exhaust cylinder steam, and is thus not drawn from the boiler proper.

The consumption of steam by the jet should not exceed 5% of the total steam output of the boiler, although after long periods of operation, the jet orifices become enlarged and the steam consumption may increase beyond practical bounds.

Forced Draught.

The principle of the forced draught system is to supply air under pressure into a closed stokehold below the fire, a chimney being used to exhaust the flue gases as before. The air may be supplied either by a fan or by steam jets, the latter being used extensively on horizontal internal-flue boilers of the Lancashire type.

The big advantage of the steam-jet system is cheap initial cost, while its disadvantages are high steam consumption after long periods of use, and excessive moisture passing through the fuel bed decreases furnace temperature, lowers combustion efficiency, and encourages corrosive action.

Balanced Draught.

The ideal draught system is the balanced draught method, the object of which is to secure approximately zero pressure above the fire-bed, resulting in reduced leakage of cold air through the furnace brickwork, no emission through firedoors and observation ports, little tendency to stratification in the combustion chamber (*i.e.*, better gas and air mixing), and an all-round increase in combustion efficiency.

To attain this, an induced draught fan, mounted between the furnace outlet and the chimney, draws the gases through the flues, while a forced draught fan propels air in through the fuel bed, giving a draught in the region of 0.05 inches W.G. in the combustion chamber.

Advantages of Mechanically-Propelled Draught.

The advantages ensuing from the employment of mechanically-operated draught plant may be summarized thus :—

- (i) Greater flexibility of furnace.
- (ii) Higher furnace temperature—increase in efficiency.
- (iii) Lower grades of fuel may be used.
- (iv) Increase in heat release.
- (v) Chimney size dependent on site requirements only—employed to convey gases to atmosphere and not as a draught producer.

Against these points must be reckoned the disadvantages of higher initial cost, and maintenance charges on the draught plant itself, together with increased furnace maintenance due to the heavier working conditions.

Primary and Secondary Air.

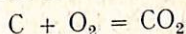
Air for combustion which is admitted with the fuel, or directly to the fuel, is termed "primary" air. With liquid, gaseous, and

pulverised fuels, this air is supplied with the fuel and mixes with it before entering the furnace proper. In the case of solid fuels, primary air is admitted through the fuel bed.

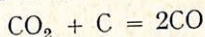
"Secondary" air is the additional air required for complete combustion, admitted with solid fuels above the fire-bed, and with other fuels from a port alongside the fuel burner. Some secondary air often leaks through to the upper side of the fire-bed, round the sides and back of the grate, etc.

The mixing of the air and fuel thus takes place in two stages. A third stage, "tertiary" air is often used, particularly in pulverised fuel firing.

A fuel bed may be divided into three distinct zones. The lowest zone, just above the grate-bars, is the ash zone. Above this is the oxidation zone, where the oxygen of the air reacts freely with the hot carbon to form carbon dioxide directly, viz. :—



If the fire-bed is deep, this CO_2 passing through further layers of hot carbon, is reduced to carbon monoxide :—



The carbon monoxide thus formed requires secondary air to burn it.

Above the oxidation zone is the zone of distillation. "Green," or raw, fuel thrown on to the fire is carbonised, giving off its tarry, gaseous matter into the combustion space above the fire, where secondary air must be supplied to consume it.

In the case of low-volatile fuels, like coke, there is no distillation zone, and consequently little or no secondary air may be required.

Thus correct fuel and air mixing is dependent on the supply of primary and secondary air, and the relationship between these must be carefully considered. Sufficient total air must be admitted to ensure completing the combustion process in the correct place and at the correct time.

The employment of excess quantities of air is one of the most important factors operating against efficient combustion. Not only does this air require heating up to the prevailing furnace temperature, probably necessitating increased fuel firing, but a more important fact is the increase in the volume of the flue gases, causing an important loss of heat content.

Consequently, only the exact amount of air required to completely consume the fuel should be supplied.

Time, Temperature and Turbulence.

Having supplied and introduced the correct quantity of air for combustion into the furnace, the important factors of time, temperature, and turbulence should be considered.

Time is obviously important for the combustion to be completed. If the space for combustion be too small, much air will pass through in an unburnt condition, resulting in increased oxygen content in the flue gases. The size of combustion chamber, therefore, is of prime importance. It should be large enough to enable correct mixing of the air and gaseous matter, before the gases pass on to the flues.

As combustion is a series of chemical reactions, and as such reactions may be accelerated by increased temperature, thus, temperature consideration is also important. A high temperature is necessary if combustion is to be completed at all, thus preheating of both primary and secondary air will aid this factor. A low furnace temperature will slow up combustion considerably, and will allow the hydrocarbons to come into contact with relatively cold surfaces before they are consumed. The result is the formation of heavy black smoke, and a consequently low combustion efficiency, not to mention the undesirability of heavy black smoke pouring from the stack.

Correct gas and air mixing can only be accomplished with turbulent flow. Streamline flow will result in stratification in the gases, and parallel bands of air and gas require considerable time to diffuse into each other. With turbulent flow, however, the air and gas are readily mixed in a comparatively small volume, so that the necessity for bringing the oxygen and unconsumed gases together as soon as possible, is thereby satisfied.

The main principles to secure efficient combustion may thus be summarized as follows :—

- (i) Sufficient, but not excessive, air for combustion should be admitted.
- (ii) Sufficiently large combustion chamber for gases and air to mix before passing on to the flues.
- (iii) Turbulence to encourage gas mixing.
- (iv) High furnace temperature, with preheated primary and secondary air.
- (v) Minimum leakage of cold air into furnace through firing doors, ash-pit doors, and faulty brickwork.

HEAT LOSSES.

Calculation of Heat Lost in Flue Gases.

- (i) Heat carried away by products of combustion.

= Wt of products $\times$ mean specific heat $\times$ temperature rise above inlet conditions.

$$= W \times 0.24 (T - t).$$

Where T = flue gas temperature $^{\circ}\text{F}$.

t = boiler room temperature $^{\circ}\text{F}$.

(assuming no air preheating).

- (ii) Heat lost due to excess air in flue gases.

$$= W \times 0.238 (T - t).$$

Where W = wt. of excess air per lb. T = flue gas temperature $^{\circ}\text{F}$. t = air inlet temperature $^{\circ}\text{F}$.

(i.e., boiler room temperature if no preheating).

- (iii) Heat lost due to moisture in products.

$$= W \{ (212 - t) + 970 + 0.48 (T - 212) \}.$$

Where W = total moisture + (hydrogen $\times 9$). t = coal temperature as fired $^{\circ}\text{F}$. T = flue gas temperature $^{\circ}\text{F}$.0.48 = mean specific heat of superheated steam at N.T.P. (60°F , 30" bar).**Heat Lost due to Unburnt CO.**

Heat lost due to unburnt carbon, producing CO in flue gases

$$= \left\{ 10,150C \times \frac{\text{CO}}{\text{CO}_2 + \text{CO}} \right\} \text{ B.Th.U. per lb. of fuel.}$$

where C = percentage of carbon in fuel. CO = " by volume of CO in flue gases. CO_2 = " " " " " " " " " " " "

10,150 is the approximate difference in heat release between burning 1 lb. of fuel completely to carbon dioxide, or incompletely to carbon monoxide.

Heat lost due to Unburnt Carbon in Ash and Riddlings.

Loss due to unburnt carbon in ash and riddlings

$$= \left\{ \frac{A \times B}{10,000} \times 14,580 \right\} \text{ B.Th.U./lb. of fuel.}$$

where A = percentage of ash and riddlings. B = percentage of carbons in ash and riddlings.**Heat Lost due to Ash in Fuel.**

This may be approximately determined from the formula :—

$$\text{Loss} = \left\{ \frac{W \times (T - t) \times \text{S.H.} \times 100}{\text{C.V. of fuel}} \right\} \%.$$

where W = weight of ash per lb. of fuel. T = temperature of ash $^{\circ}\text{F}$. t = boiler room temperature $^{\circ}\text{F}$.

S.H. = mean specific heat of ash.

Heat Balance.

To draw up a heat balance for a furnace, a knowledge of the following figures is necessary :—

- (i) "Ultimate" analysis of the fuel.
- (ii) Higher calorific value of the fuel (determined by bomb calorimeter.)
- (iii) Fuel consumption per hour.
- (iv) Analysis of dry flue gases (by volume).
- (v) Temperature of flue gases at furnace outlet.
- (vi) Mean specific heat of flue gases.
- (vii) Boiler room temperature.
- (viii) Overall thermal efficiency

$$= \frac{\text{heat recovered per lb. of fuel as fired}}{\text{H.C.V. of fuel (determined by bomb calorimeter)}}$$

From the foregoing, the heat carried away by the flue gases, heat lost due to traces of CO in the flue gases, heat lost due to unburnt carbon in ash and riddlings, and heat lost due to ash in the fuel may be determined. These will be accompanied by unaccountable losses due to radiation, etc., and each loss may be expressed as a percentage of the initial heat supplied, giving a clear indication of excess heat loss in any section of the plant.

SOLID FUEL FIRING.

Hand-Firing.

With hand-firing, the efficiency of combustion depends solely on the fireman, and as hand-firing must necessarily be an intermittent process involving considerable opening and closing of the fire-doors, careful operation of the furnace is necessary to obtain efficient combustion of the fuel.

The three methods of hand-firing are :—

- (i) Spreading or sprinkling—in which an even layer of fuel is fed over practically all the grate area.
- (ii) Side or wing firing—in which the fuel is fed to right and left of the furnace alternatively.
- (iii) Coking—in which the fuel is fed to the front of the grate, and the volatile matter allowed to be driven off before the fuel is spread over the whole grate.

The above methods also apply to mechanical stoker firing, as well as hand-firing, as will be seen later.

It is most necessary, with hand-firing, that the depth of fuel bed should be consistent with the load required from the boiler. Rapid steam-raising requires a thin fire, and while a thick fire is necessary for the greatest economy it should be evenly spread over the grate to allow good air penetration. All hollows should be

levelled out, as patches of thin fire will result in a large blow-through of cold air. Efficient manipulation of the slicing tool to clear adherent clinker is also necessary for correct air distribution, as well as the breaking-up of large masses of caked fuel.

The design of the grate itself, upon which the air distribution is primarily dependent, is an important factor. Various patent types of grate are in service, ranging from the plain firebar to the zoned grate, in which each zone has its own regulating damper operated by the velocity of the incoming air.

Hand-firing, these days, is confined to some types of marine boiler, locomotive boilers, and the small industrial steam plant, where the heat release required is not sufficient to warrant the installation of mechanical firing methods.

The Mechanical Stoker.

Mechanical stokers may be grouped in several ways. Reference to Table V., which shows the various types of stoker in use to-day, indicates several methods of grouping. Perhaps the best method is to consider them from the point of application, *i.e.* :—

- (i) Stokers for internal-flue boilers.
- (ii) „ „ water-tube boilers.

These may be sub-divided into :—

- (i) Underfeed firing.
- (ii) Overfeed firing.

and further sub-divided into the methods of fuel delivery as outlined under the section on hand-firing.

In the case of “underfeed” firing, the raw fuel is fed to the fire from below, while with “overfeed” firing, the fuel may either be delivered at the front of the fire, or spread evenly over the whole fire-bed.

The definite advantages to be gained from the use of automatic stokers are :—

- (i) Even feeding of the fuel to the fire.
- (ii) Even distribution of combustion air.
- (iii) Minimum smoke formation.
- (iv) Better furnace control.
- (v) Greater heat release per square foot of grate area.

Stokers for Internal Flue Boilers. .

(i) **Sprinkler Stokers.**—These, as their name implies, sprinkle the fuel over the grate surface by means of high-speed rotary distributor blades, or swinging shovels.

Sprinkler stokers employing rotary distributors usually have a fixed grate, and the fuel is spread evenly and continuously over the whole grate to a depth of 2 to 4 inches according to coal size.

TABLE V.
TYPES OF STOKERS.

Type of Stoker.	Type of Fuel Feeding.	Application.	Type of Grate.
UNDERFEED	"Underfeed"	Internal Flue Boilers Small Industrial Furnaces Small Water-tube Boilers	Fixed Grate
	"Retort"	Water-tube Boilers	Agitated Grate
OVERFEED	"Sprinkler"	Internal Flue Boilers	Fixed Grate
	"Coking"	" " "	Agitated Grate
	Travelling Grate	Water Tube Boilers	Travelling Grate
	"Spreader"	" " "	Dumping Grate
	"Spreader"	" " "	Travelling Grate

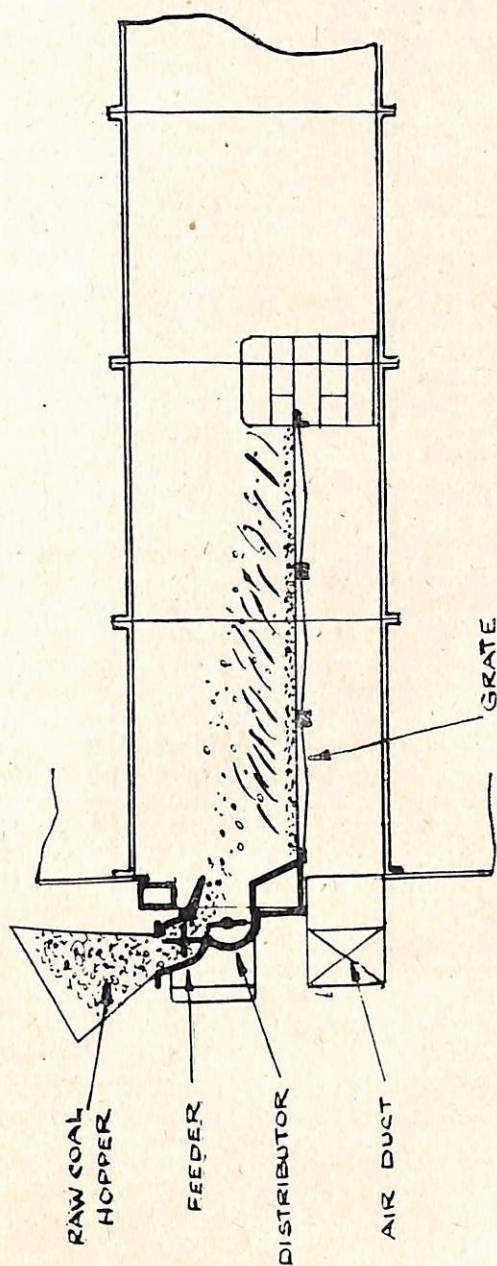


Fig. 1—Sprinkler Stoker.

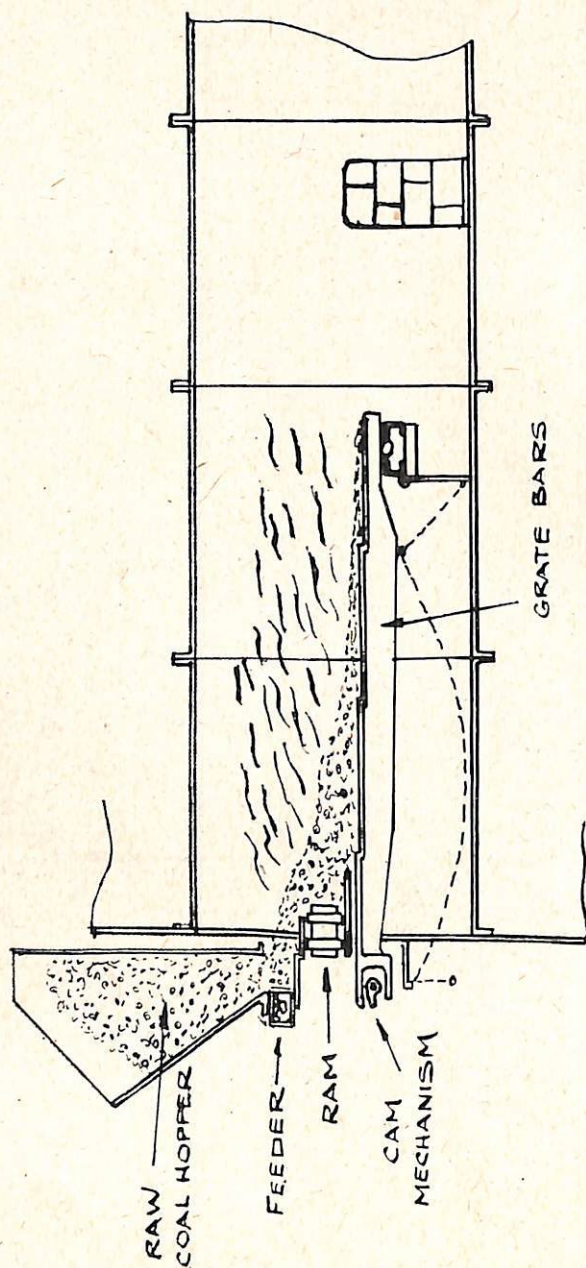


Fig. 2—Coking Stoker.

The swinging shovel type is intermittent in operation, and the grate-bars are usually agitated by a cam mechanism to give a self-cleaning action. The fire thickness is usually thicker than the rotary distributor type.

Fig. 1 gives a diagrammatic arrangement of a sprinkler stoker employing rotary distributors, applied to a Lancashire-type boiler.

One important point in regard to the sprinkler stoker is the tendency for excessive grits in the flue gases, due to the method of fuel firing; this is overcome to some extent by regulating the speed of the distributor to give a "throw" suitable to the coal being fired.

(ii) **Coking Stokers.**—This stoker (Fig. 2) imitates the "coking" method of firing, the coal being pushed into the front of the furnace by a cam-operated ram. The volatiles are distilled off at the front end of the furnace and pass along over the hot bed of coke further back, where they are consumed. Grit emission is thus reduced to a minimum. The fire-bed is usually about 12 inches thick at the front, tapering off towards the rear end, and consequently, the thicker fire-bed of this type of stoker requires a stronger draught than the sprinkler type.

(iii) **"Underfeed" Stokers.**—Fig. 3 illustrates what is usually termed the "pot" type of underfeed stoker, applied to a vertical boiler. A second type, known as the grate type, is similar in arrangement, but the retort is semi-circular in cross-section suitable for mounting in the circular flues of the Lancashire and economic type of boiler.

The raw coal is delivered from the hopper to the underside of the fire-bed by a worm, or feeder screw; the volatiles, distilled from the coal at the bottom of the retort, passing up through the top layer of incandescent coke, where complete combustion occurs. Air for combustion is introduced through tuyeres surrounding the retort.

Stokers for Water-Tube Boilers.

(i) **Travelling-Grate Stokers.**—The travelling-grate, or chain-grate, stoker is of the "coking" variety, the raw fuel being delivered at the front. The distilled gaseous matter passes along above the incandescent coke, where with the addition of secondary air, it is smokelessly consumed.

Fig. 4 shows a typical arrangement of a travelling-grate stoker with auxiliary equipment, as applied to a large capacity water-tube boiler.

The grate itself is composed of longitudinally or transversely arranged links suitably attached to several endless chains passing over driving sprockets at the front shaft, and loose rollers, or skids, at the rear. The primary air is admitted through the fine-ash hopper as shown, and passes through the returning chain into the

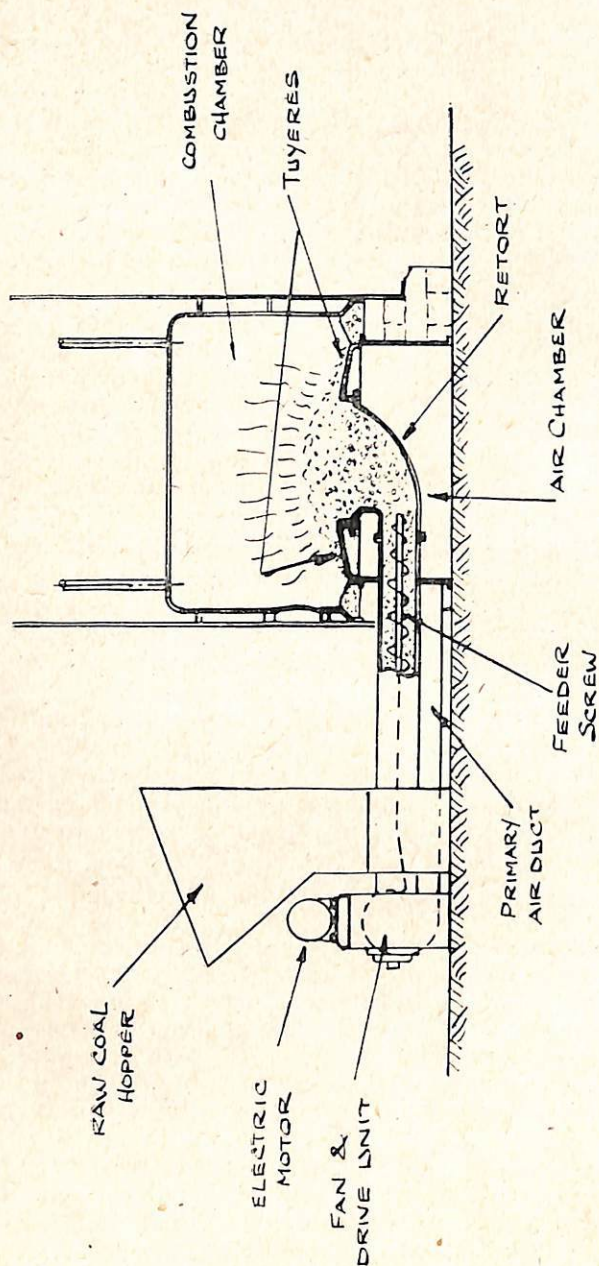


Fig. 3—Underfeed Stoker applied to Vertical Boiler.

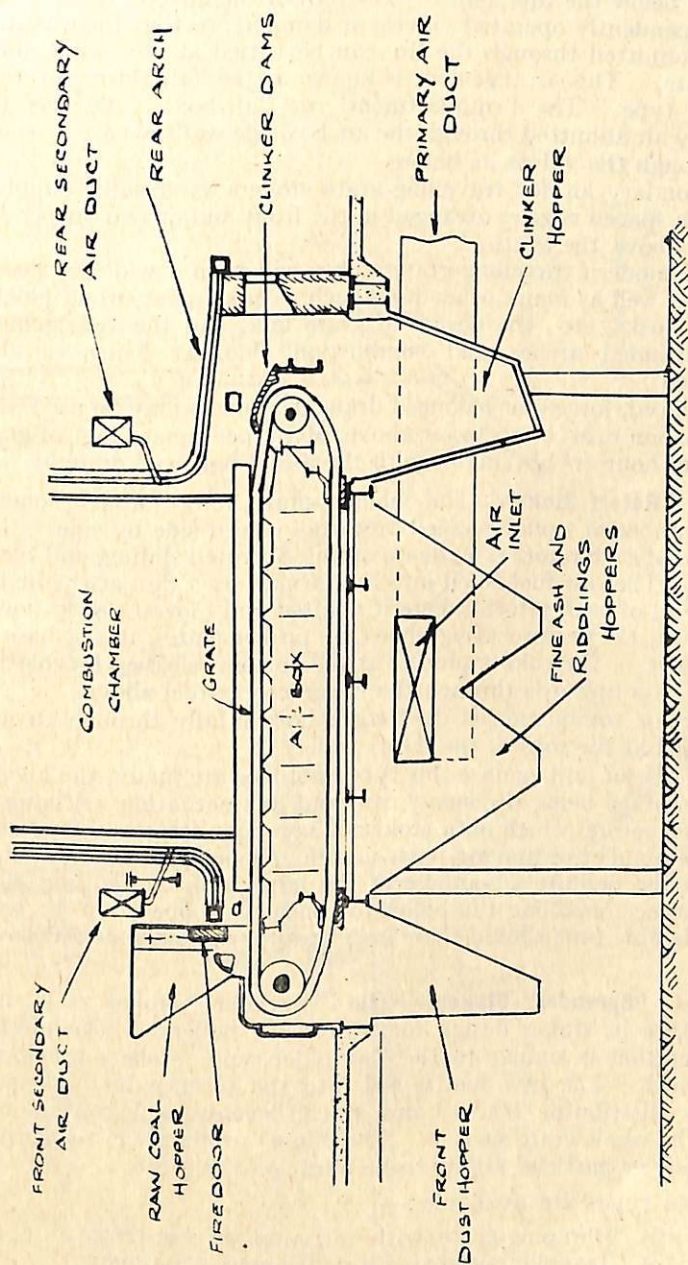


Fig. 4—Travelling Grate Stoker applied to Water-Tube Boiler.

air-box below the top chain. The roof of the air-box is composed of independently operated valves, or dampers, so that the quantity of air admitted through the fire can be varied at any point along the grate. This arrangement is known as the "air through return chain" type. The "compartment" or "air-box" type has the primary air admitted through the air-box side walls, where it passes up through the valves as before.

Secondary air for travelling-grate stokers is usually supplied through spaced nozzles arranged in the front and/or rear suspended arches above the grate.

The modern travelling-grate stoker will burn a wide variety of coals, as well as many other fuels such as coke, peat, wood blocks, paddy husks, etc., the design of grate link, and the arrangement of suspended arches and combustion chamber being suitably arranged.

Induced, forced, or balanced draught systems may be used, and combustion rates of up to, or above, 50 lb. per square foot of grate area per hour are obtainable with the use of balanced draught.

(ii) **Retort Stoker.**—The inclined-grate retort stoker consists of a number of trough-shaped "retorts" placed side by side. The bottom of each retort is made up of link-operated sliding, and fixed, shoes. The raw fuel is fed into the furnace by a ram at the higher front end of each retort, where it is lifted and moved slowly downwards by the reciprocating shoes, or pusher-plates at the base of the retort. The coking process at the bottom releases the volatiles which pass upwards through the incandescent fuel above.

Air for combustion is discharged horizontally through tuyeres arranged at the tops of the retort walls.

Points for and against this type of stoker are many, the biggest disadvantage being the heavy cam and link actuating mechanisms for each retort, which on a stoker of say eight retorts wide, means a large number of moving parts needing servicing. Counteracting this is the definite advantage of the large bulk of fuel always in the furnace, enabling the boiler to continue in operation for some considerable time should there be a breakdown in the coal delivery plant.

(iii) **"Spreader" Stokers.**—The "spreader" stoker is a new departure in stoker design for water-tube boilers. The method of operation is similar to the "sprinkler-type" stokers previously described. The raw fuel is fed into the furnace by high-speed rotary distributor blades, and spread evenly and continuously over the whole grate surface. The "fines" are burnt in suspension, the heavier particles falling to be burnt on the grate.

Two types are available :—

- (i) Dumping-grate with sectionalised ash-removal.
- (ii) Travelling-grate with continuous ash-removal.

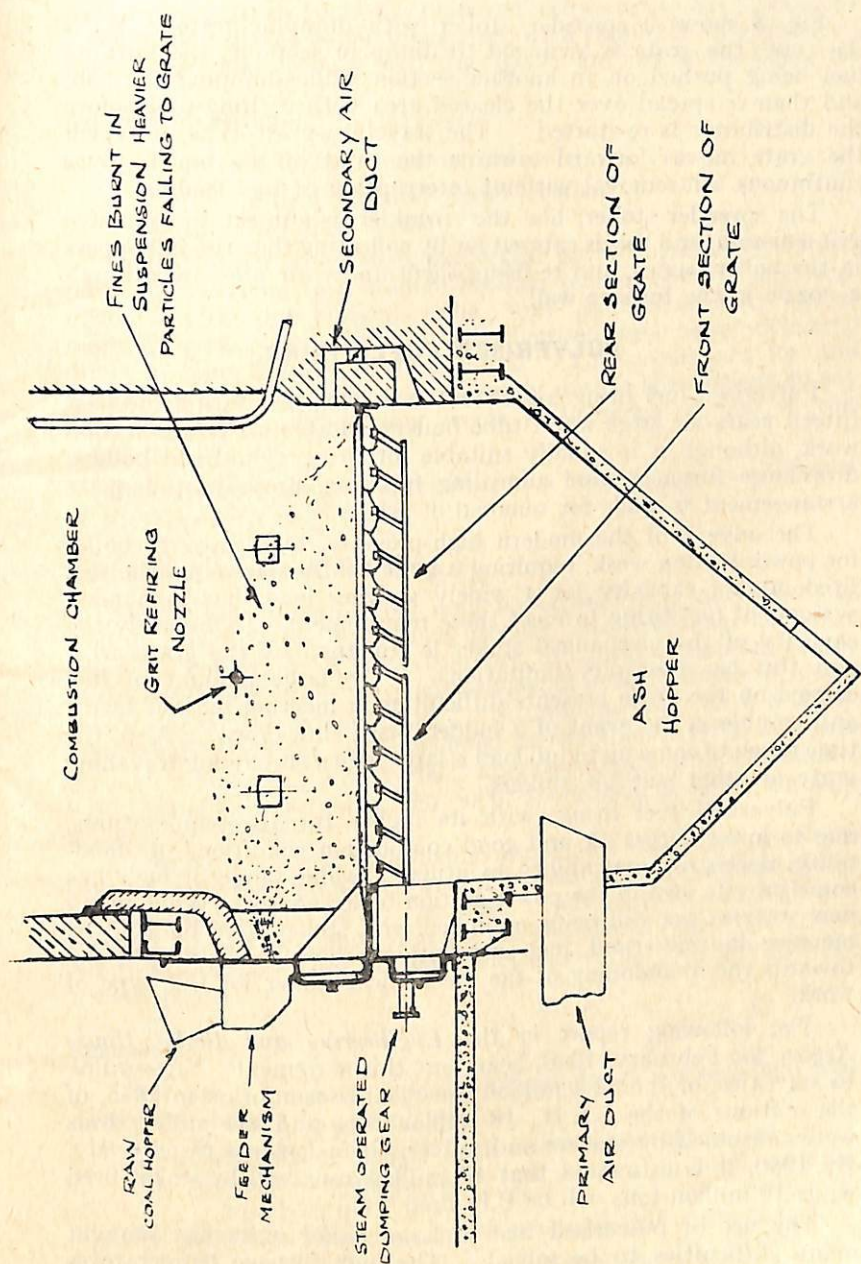


Fig. 5—Spreader Stoker with Dumping Grate.

Fig. 5 shows a spreader stoker with dumping-grate. With the type, the grate is arranged to dump in sections, the burning fuel being pushed on to another section while dumping the ash, and then re-spread over the cleared area with a firing-tool before the distributor is re-started. The travelling-grate type, in which the grate moves forward towards the front of the boiler, gives continuous ash-removal without interruption of fuel feeding.

The spreader stoker, like the sprinkler, is subject to excessive grit emission, and this is catered for by collecting the grits in hoppers in the boiler passes, and re-firing them under air pressure through a nozzle in the furnace wall.

PULVERISED FUEL FIRING.

Pulverised fuel firing has shown increasing use during the past fifteen years for large water-tube boilers suitable for power-station work, although it is equally suitable for firing cylindrical boilers, drop-forge furnaces, and annealing furnaces, providing adequate arrangement is made for removal of ash.

The advent of the modern high-pressure, high-capacity boiler for power-station work, requiring a large heat-release from the fuel fired, and a capacity for a widely varying load, has demanded systems of fuel firing to meet these requirements. Obviously the capacity of the mechanical stoker is governed by the grate area, and this has necessary limitations. The large amount of fuel carried on the grate presents difficulties in meeting variant loads, and trouble in the event of a sudden plant shut-down. Also, the time taken to come up to full load is large, when employing travelling grate or other suitable stokers.

Pulverised fuel firing, with its higher furnace temperatures, due to lower excess air and good combustion conditions, its flexibility of control, and ability to utilize a wider range of fuels has come into its own in the power station boiler-house. While many new stations are still being equipped with stoker fired boilers, the increase in pulverised fuel installations shows a definite trend towards the abandoning of the mechanical stoker for this type of work.

The following report in the *Engineering and Boiler House Review* for February, 1948, bears out this statement. "According to statistics, of the 22.4 million tons coal consumption in 1945, of the stations of the C.E.B., 18 million tons and 4.4 million tons were consumed by stokers and pulverised fuel plants respectively. By 1950, it is estimated that 17 million tons will be stoker-fired while 10 million tons will be P.F. fired."

The use of pulverised fuel in large boiler units has brought many difficulties to be solved. The high furnace temperatures involved have made necessary the use of furnace wall cooling

media, as well as specially prepared refractories and insulation. Bare, widely-spaced water-tubes, and tubes protected by refractory-loaded, and smooth-faced cast-iron blocks are now in common use.

Systems of Firing.

Two systems of firing are in use :—

- (i) Central bin and feeder system.
- (ii) Unit mill system.

In the former, the fuel is pulverised by a centrally-placed mill unit and delivered to a storage bunker, several boilers being supplied from the one bunker. The "unit" system employs one or more pulverisers per boiler, the pulverised fuel being delivered direct to the burners from the mill. The arguments for and against each of these systems are many, but it is sufficient to say here that the "unit" system seems to be more popular in this country.

Figs. 6 and 7 are flow-sheet diagrams indicating typical layouts of the two systems.

Fuel and Fineness of Grinding.

Almost all grades of coal may be satisfactorily pulverised, as well as certain other fuels such as peat, and solid coal tar fuels. The ideal conditions of pulverising are, of course, maximum degree of fineness ; but, from the point of view of overall plant efficiency, this is not considered necessary. Bituminous coals with a fairly high volatile content are considered satisfactory if 70% will pass through a 200-mesh screen ($\cdot 003''$ aperture), and with anthracite, 95% through a 100-mesh screen ($\cdot 006''$ aperture), and 85% through a 200-mesh screen.*

Coals with a very high ash content, or very high moisture content have been employed on P.F. installations, although excess in either is undesirable. The dust, resulting from the high ash content, has to be removed from the flue gases before they pass out to atmosphere, and excessive moisture in the flue gases incurs wasted heat.

Furnaces.

There are three main types of furnace for pulverised fuel fired water-tube boilers in general use :—

- (i) Flat bottom furnace—ash removal by raking out.
- (ii) Hopper bottom furnace—ash removal in solid or semi-liquid state.
- (iii) Slag-tap furnace—ash removal in liquid state only.

**Steam Boiler Yearbook*, 1944. Paul Elek (Publishers), Ltd.

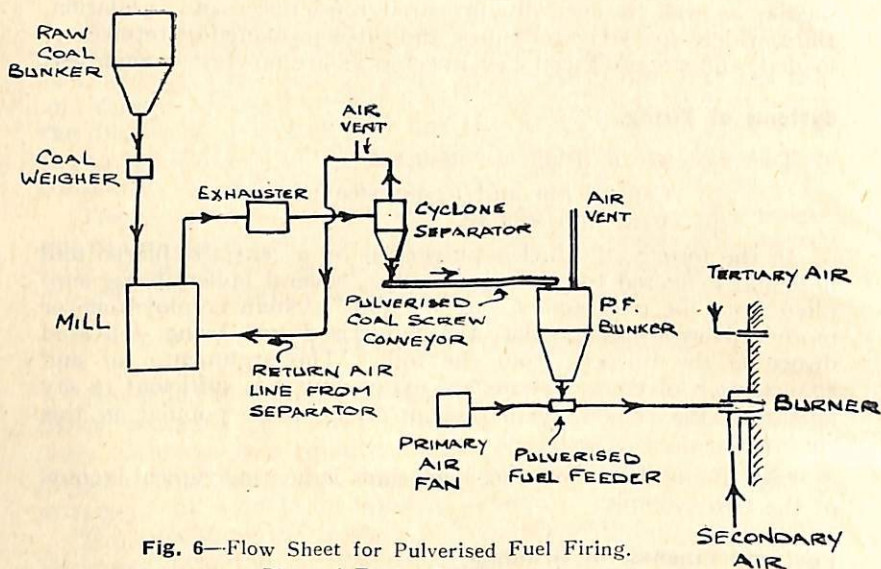


Fig. 6—Flow Sheet for Pulverised Fuel Firing.
Bin and Feeder System.

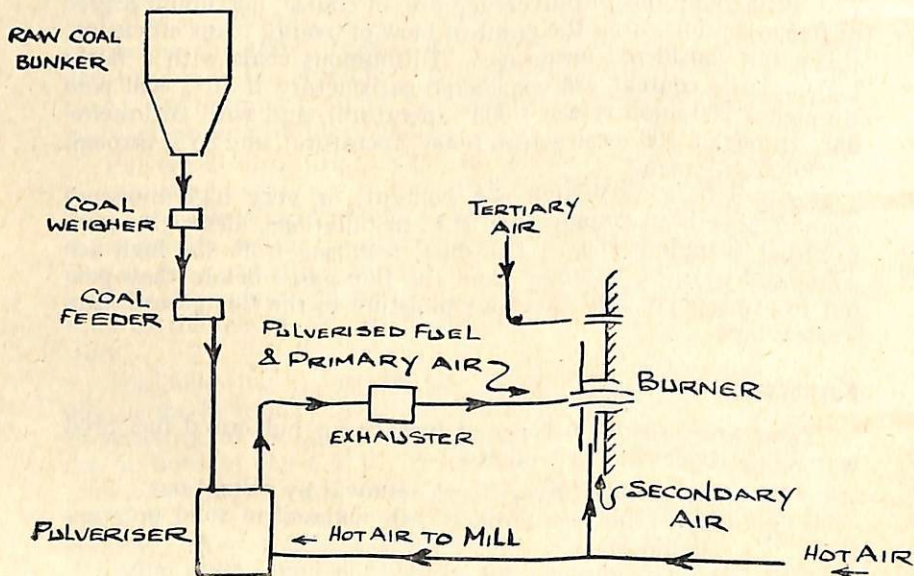


Fig. 7—Flow Sheet for Pulverised Fuel Firing. Unit System.

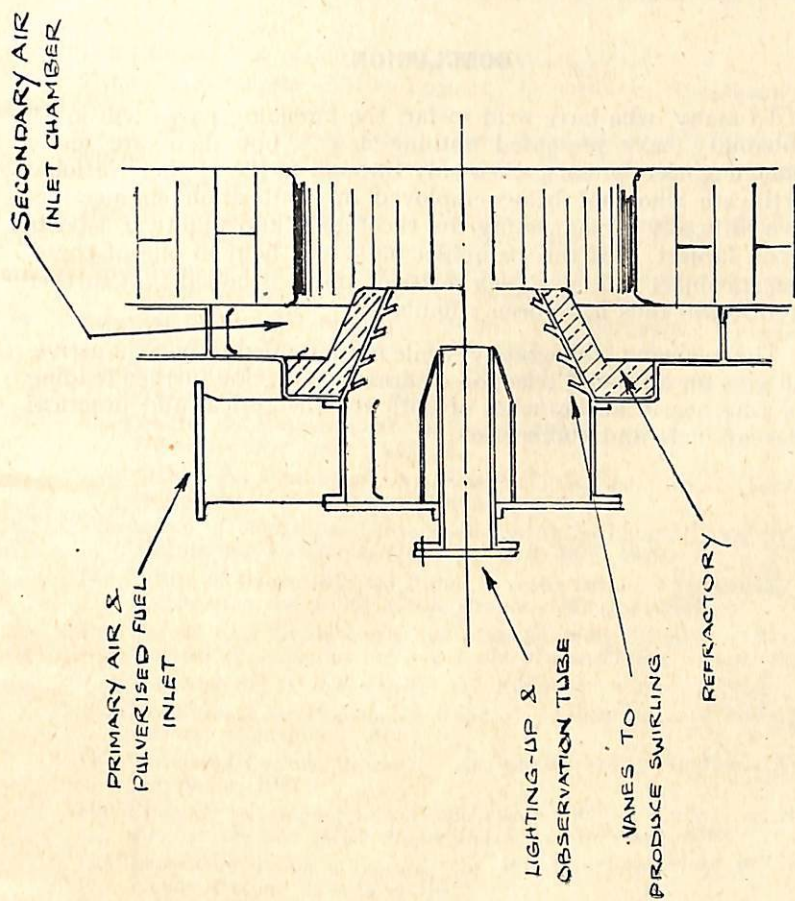


Fig. 8—Typical Pulverised Fuel Burner.

Burners.

Fig. 8 gives a diagrammatic arrangement of a typical pulverised fuel burner. There are several designs of burner on the market, but all follow the general principles indicated in the figure. Several types incorporate special vanes on the air and fuel inlets to promote a swirling effect in the furnace, and so to encourage intimate fuel and air mixing.

CONCLUSION.

To many, who have read so far, the foregoing pages will in all probability have presented nothing new; but there are many young engineers pressing their way through to the Higher National Certificate who, not being employed in combustion engineering, have difficulty in connecting the theoretical and practical aspects of the subject. If this pamphlet has given help to one of these, then its object will have been realised, and it is hoped that further interest will thus have been stimulated.

The following bibliography, while not intended to be exhaustive, will give an all-round selection of articles, etc., for further reading covering nearly all branches of both the theoretical and practical sides of fuels and combustion.

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List of A.E.S.D. Data Sheets.

1. Safe Load on Machine-Cut Spur Gears.
2. Deflection of Shafts and Beams.
3. Deflection of Shafts and Beams (Instruction Sheet) } Connected.
4. Steam Radiation Heating Chart.
5. Horse-Power of Leather Belts, etc.
6. Automobile Brakes (Axle Brakes) } Connected
7. Automobile Brakes (Transmission Brakes) }
8. Capacities of Bucket Elevators.
9. Valley Angle Chart for Hoppers and Chutes.
10. Shafts up to $5\frac{1}{2}$ -in. diameter, subjected to Twisting and Combined Bending and Twisting.
11. Shafts, $5\frac{1}{2}$ to 26-inch diameter, subjected to Twisting and Combined Bending and Twisting.
12. Ship Derrick Booms.
13. Spiral Springs (Diameter of Rd. or Sq. Wire).
14. Spiral Springs (Compression).
15. Automobile Clutches (Cone Clutches).
16. " " (Plane Clutches).
17. Coil Friction for Belts, etc.
18. Internal Expanding Brakes. Self-Balancing Brake Shoes (Force Diagram) }
19. Internal Expanding Brakes. Angular Proportions for Self-Balancing } Connected
20. Referred Mean Pressure Cut-Off, etc.
21. Particulars for Balata Belt Drives.
22. $\frac{3}{4}$ " Square Duralumin Tubes as Struts.
23. 1" " " " (30 " ton yield).
24. $\frac{1}{4}$ " Sq. Steel Tubes as Struts (30 ton yield).
25. $\frac{3}{8}$ " " " " (30 ton yield).
26. 1" " " " (40 ton yield).
27. $\frac{3}{4}$ " " " " (40 ton yield).
28. $\frac{7}{8}$ " " " " (40 ton yield).
29. 1" " " " (40 ton yield).
30. Moments of Inertia of Built-up Sections (Tables) }
31. Moments of Inertia of Built-up Sections (Instructions and Examples) } Connected.
32. Reinforced Concrete Slabs (Line Chart) }
33. Reinforced Concrete Slabs (Instructions and Examples) } Connected.
34. Capacity and Speed Chart for Troughed Band Conveyors.
35. Screw Propeller Design (Sheet 1, Diameter Chart)
36. " " " (Sheet 2, Pitch Chart) }
37. " " " (Sheet 3, Notes and Examples) } Connected.
38. Open Coil Conical Springs.
39. Close Coil Conical Springs.
40. Trajectory Described by Belt Conveyors.
41. Metric Equivalents.
42. Useful Conversion Factors.
43. Torsion of Non-Circular Shafts.
44. Railway Vehicles on Curves.
45. Chart of R.S. Angle Purlins.
46. Coned Plate Development.
47. Solution of Triangles (Sheet 1, Right Angles).
48. Solution of Triangles (Sheet 2, Oblique Angles).
49. Relation between Length, Linear Movement and Angular Movement of Lever (Diagram and Notes).
50. " " " " " " (Chart).

51. Helix Angle and Efficiency of Screws and Worms.
52. Approximate Radius of Gyration of Various Sections.
53. Helical Spring Graphs (Round Wire)
54. " " " (Round Wire) } Connected.
55. " " " (Square Wire)
56. Relative Value of Welds to Rivets.
57. Ratio of Length/Depth of Girders for Stiffness.
58. Graphs for Strength of Rectangular Flat Plates of Uniform Thickness.
59. Graphs for Deflection of Rectangular Flat Plates of Uniform Thickness.
60. Moment of Resistance of Reinforced Concrete Beams.
61. Deflection of Leaf Spring.
62. Strength of Leaf Spring.
63. Chart showing Relationship of Various Hardness Tests.
64. Shaft Horse Power and Proportions of Worm Gears.
65. Ring with Uniform Internal Load (Tangential Strain) } Connected.
66. Ring with Uniform Internal Load (Tangential Stress)
67. Hub Pressed on to Steel Shaft. (Maximum Tangential Stress at Bore of Hub).
68. Hub Pressed on to Steel Shaft. (Radial Gripping Pressure between Hub and Shaft).
69. Rotating Disc (Steel) Tangential Strain } Connected.
70. " " " Stress
71. Ring with "Uniform" External Load, Tangential Strain } Connected.
72. " " " Stress
73. Viscosity Temperature Chart for "Converting" Commercial to Absolute Viscosities } Connected.
74. Journal Friction on Bearings
75. Ring Oil Bearings
76. Shearing and Bearing Values for High Tensile Structural Steel Shop Rivets, in accordance with B.S.S. No. 548/1934 } Connected.
77. Permissible Compressive Stresses for High Tensile Structural Steel, manufactured in accordance with B.S.S. 548/1934.
78. Velocity of Flow in Pipes for a Given Delivery } Connected.
79. Delivery of Water in Pipes for a Given Head
80. Working Loads in Mild Steel Pillar Shafts.
81. Involute Toothed Gearing Chart.
82. Steam Pipe Design. Chart showing Flow of Steam through Pipes.
83. Variation of Suction Lift and Temperature for Centrifugal Pumps.
84. Nomograph for Uniformly Distributed Loads on British Standard Beams
85. " " " " " " }
86. " " " " " " } Connected.
87. Notes on "Beam Design and on "Use of Data Sheets, Nos. 84-5-6.
88. " " " " " " }
89. Curve Relating Natural Frequency and "Deflection"
90. Vibration Transmissibility Curve for Elastic Suspension } Connected.
91. Instructions and Examples in the Use of Data Sheets, Nos. 89 and 90
92. Pressure on Sides of Bunker.
- 93-4-5-6-7. Rolled Steel Sections.
- 98-99-100. Boiler Safety Valves.
101. Nomograph Chart for Working Stresses in Mild Steel Columns.

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